



PV String to 3-Phase Inverter with Highest Voltage Capabilities, Highest Efficiency and 25 Year Lifetime

**Final Technical Report:
November 7, 2011 – November 6, 2012**

Rick West
*Renewable Power Conversion
San Luis Obispo, California*

NREL Technical Monitor: Harin S. Ullal

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Overview

The overall objective of this project was to develop a prototype PV inverter which enables a new utility-scale PV system approach where the cost, performance, reliability and safety benefits of this new approach have the potential to make all others obsolete.

The overall results of this project were that all PV inverter cost and performance metrics were exceeded including; 98% CEC conversion efficiency, a maximum case temperature rise of 14°C under nominal conditions, Total Harmonic Distortion <5% and automatic Volt-VAR capability.

Specifically, the inverter is a modular, environmentally robust 10kW unit which converts power from one bipolar PV string to 600Vac 3-phase. A commercial or utility scale system based on these inverters would be made up of a number of distributed PV-to-AC inverters, with intra-system power collection at 600Vac. The inverter product line will be named Macro-Micro as an allegorical reference to a “microinverter” approach scaled and optimized for use in systems from 10kW to multi-megawatts.



Photograph 1 – 10kW Macro-Micro Inverter

Macro-Micro Advantages

LCOE can be reduced by 8% compared to central inverter system solutions

The inverter is designed for a maintenance-free lifetime equivalent to that of PV modules

Novel natural convection cooling and packaging methods

Novel power conversion topology

98% CEC power conversion efficiency

NEMA 6 / IP67 environmental integrity

Plug-and-play installation/replacement by unskilled personnel

Power density more than twice that of prior-art 10kW inverter approaches

600Vac 3-phase grid-tie with 480Vac and 400Vac product variants

Transformerless, single-conversion power topology

Highly scalable, lowest cost 10kW to multi-megawatt system solutions

Highly efficient 600Vac 3-phase intrafield power collection

DC fault current, fault energy and arc potential limited to that of one PV string

High MPPT granularity in commercial and utility scale systems

Single-component replacement parts inventory requirement

Low installation costs and site infrastructure requirements

Project Background

Summary Advantages and Disadvantages of Prior-Art Approaches

Essentially all multi-megawatt photovoltaic (PV) power systems use central inverter based building blocks of roughly 1MW where PV power is collected in one location to feed a ~1MW PV-to-AC power converter. The power converter is connected locally to a distribution transformer to step up low inverter output voltages to medium voltage distribution levels for final, system-level power collection. The advantage of this approach is inverter economies of scale. The disadvantages are that a single array ground fault or inverter failure will disable a megawatt of production, high energy DC arc potentials exist, maximum power point tracking accuracy is low compared to distributed power converter approaches, preventative maintenance is required, usable inverter lifetime is, at best, less than half that of the solar modules and inverter-specific site infrastructure costs are relatively high.

A second method, little used but a potentially emerging technology, is to use a number of low power PV string to DC power converters distributed throughout a ~1MW solar array field all sourcing power to a ~1MW DC-to-AC power converter and medium voltage distribution transformer. This solution provides higher DC collection voltages and therefore enhanced intrafield power collection efficiencies, provides greater PV maximum power tracking granularity and enables the DC-to-AC inverter stage to work at higher power conversion efficiencies. The disadvantages are that all central inverter related drawbacks are still in place, two-stage power conversion (PV-to-DC and then DC-to-AC) significantly limits system conversion efficiencies, system complexity is high and the cost of fuses and disconnect switches rated above 600Vdc (in most cases) and above 1000Vdc (in all cases) negate the copper conductor reduction benefits.

A third method, proposed by micro-inverter manufacturers, involves using one PV to single-phase AC micro-inverter for every solar module or for a small group of modules and where one or two tiers of intrafield 60Hz voltage step-up transformers would be required to facilitate AC power collection. This solution provides excellent system uptime because of the quasi-redundancy provided by a great number of low power inverters. Other benefits include DC arc hazard mitigation and the manufacturing potential for very high levels of power converter integration. The micro-inverter system drawbacks include inefficient, intrafield collection due to low AC inverter output voltages and/or lower tier 60Hz step-up transformer losses, high system complexity, very low component-count-based Mean Time Before Failure (MTBF) numbers for the system, higher initial \$/kW inverter costs and high system (inverter replacement) maintenance costs. In addition, single-phase micro-inverters must use short-lifetime electrolytic energy storage capacitors or incur a cost premium for bulk film-type energy storage capacitors or suffer low power conversion efficiencies.

The proposed power converter enables a novel distributed inverter system solution with essentially all the advantages and none of the drawbacks associated with these three prior-art approaches. Essentially, the power converter is a very high efficiency, single-conversion, transformerless inverter which essentially converts power from PV strings at the highest possible pole-to-pole voltages (~2000Vdc) directly to 3-phase AC at the highest possible voltage (600Vac) in the low-voltage equipment class.

Project Objectives

The following power converter product requirements have been devised to succinctly define the project objectives and work plan to create a game changing and significantly disruptive inverter technology.

Primary power converter performance requirements

The converter shall have a maintenance-free lifetime equal to the connected PV module-string lifetime.

One modular power converter shall enable system solutions with the lowest installation and maintenance costs per unit of energy produced over the life of the system for systems ranging in size from 10kW to megawatts.

Secondary and supporting power converter requirements

1. The converter shall be cooled by natural convection and shall have no moving parts, serviceable parts or parts requiring maintenance.

The power converter shall be rated for outdoor deployment to NEMA 6 and IP67.

Interior power converter electronic components shall be conformal coated to provide a 100% environmental seal.

The power converter shall use a single conversion, transformerless power topology to convert DC power to 3-phase power at 600Vac.

The minimum average weighted CEC efficiency for the power converter shall be 98%.

System-specific power converter requirements

1. DC arc hazard mitigation – The collection of DC power at any one point in a PV system of any size using the proposed inverter shall not exceed 15kWstc.

The installation or replacement of power converters shall be “plug-and-play” by one unskilled worker.

A single power converter failure in a multi-megawatt scale system shall not affect the system power output by more than 1%.

A single PV ground fault in a multi-megawatt scale system shall not affect the system power output by more than 1%.

PV maximum power tracking granularity shall be limited to a maximum of 10kWs.

Inverter Attributes Directly Aligned with DOE Interests

Low-cost modular PV inverters/components

Development of inverters that operate at higher DC and AC voltages/wiring

Higher frequency switching technologies or moving to transformer-less designs to reduce converter size and weight for inverters

Enhanced energy harvesting through new algorithms for maximum power point tracking.

PV system technologies that mitigate fire hazards and enhance safety in general.

Plug-and-play wiring and installation techniques

Inverter Attributes Indirectly Supporting DOE Interests

This project responds indirectly to other approaches of interests to DOE by providing a complete replacement for these approaches in all non-residential applications:

AC modules – small PV inverters to mount into a single or small group of modules

Development of low cost DC converters to boost DC voltages from modules or strings of modules

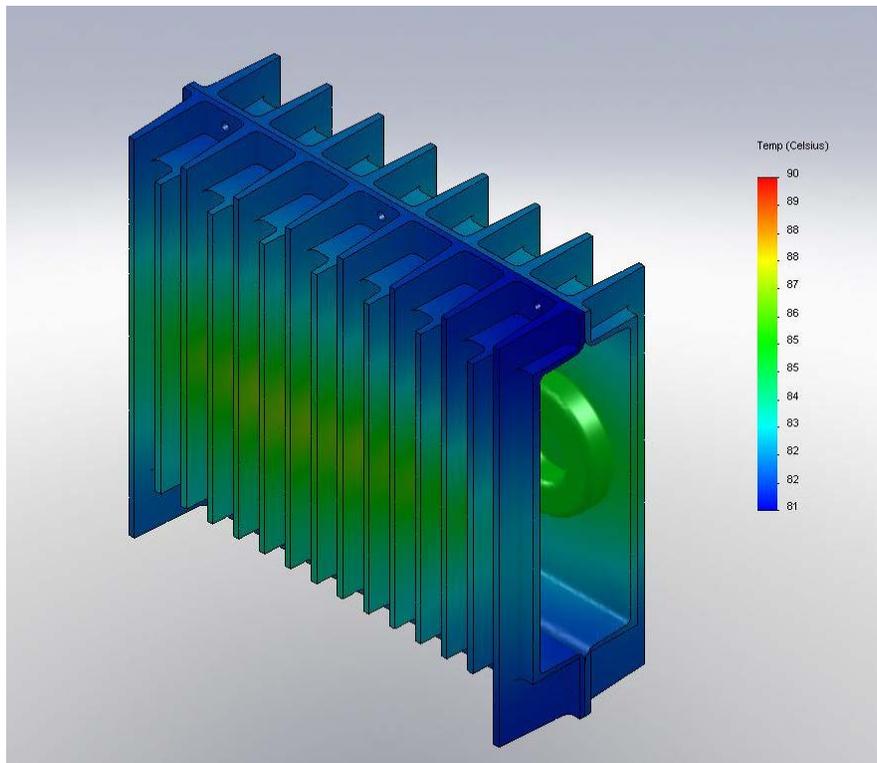
Project Tasks and Results

Task 1 - Inverter Baseline Quantification

The subcontractor developed a proof-of-concept thermal model based on an optimized enclosure design and using resistive loads having the exact same form factor and mounting method as will be used in the prototype inverter. In addition, the subcontractor developed a 3D SolidWorks computer thermal model that will corroborate the physical model data. Simulated losses were based on a detailed loss analysis of the inverter under nominal conditions.

The subcontractor completed a comparative LCOE system analysis between a 10MW central-inverter-based system and a 10MW system using the 10kW macro-micro inverter. The analysis showed that an 8% reduction in the LCOE could be expected using the distributed macro-micro inverter approach based on the proven performance, cost and anticipated lifetime of the 10kW inverter. Data from the computer thermal model and the LCOE comparison were presented in the first quarterly report.

The thermal proof-of-concept hardware was fully tested and achieved the following performance goals: chassis temperature under simulated normal conditions (8kW, 1150Vdc, 20°C ambient, 1m/s wind) measured top center of chassis <50°C or <30°C rise from ambient; chassis temperature under simulated worst case conditions (10kW, 900Vdc, 50°C ambient, 1m/s wind), measured top center of chassis <90°C or <40°C rise from ambient; calculated highest temperature semiconductor junction under normal conditions <100°C (represents 50°C) margin; and calculated highest temperature semiconductor junction under worst case conditions <125°C (represents 25°C) margin.



Thermal Model 1

Task 2 – Inverter Prototype Design

In this Task, the subcontractor completed the prototype inverter design including all the formal documentation required to manufacture the inverter prototype including a System Architecture Block Diagram, a Hardware Layout Drawing, a Functional Specification, Electrical Schematics, Bills of Materials, PCB Layouts, Magnetic Component Fabrication Drawings and Mechanical Component Fabrication Drawings. The subcontractor also procured component parts for six prototype inverters and fully assembled two inverter prototypes for a 10kW, 600Vac, 1800Vdc inverter employing a PV-specific three level neutral point clamp (3LNPC) switching topology. This inverter prototype development included; (i) all formal support documentation, (ii) an updated, detailed loss analysis which indicated >98% CEC average weighted conversion efficiency, (iii) an updated costed BOM which supports a total parts cost of <\$0.10 per Watt in 1000 unit quantities based on vendor quotations and (iv) printed circuit boards which met the voltage clearance requirements per the subcontractor supplied voltage map and spacing table.

This task resulted in two complete, but non-functional, inverter prototypes ready to serve as target hardware for the software design task, Task 3 and thereafter Design Verification Testing (DVT) in Task 4. This task consisted of four subtasks.

Subtask 2.1 – Functional Specification (FS)

This Task resulted in a detailed product definition with respect to physical attributes, performance, features, functions and regulatory compliance. This document served and serves as a “map” to keep the product development team aligned and working efficiently. This Functional Specification also includes software requirements and product reliability design rules. A System Architecture Block Diagram and a Hardware Layout Drawing based on the Functional Specification were also produced.

For reference, the following minimum requirements were initially specified in Task 2 as shown in Table 1 and were met or exceeded in Task 4:

Table 1 – Minimum Inverter Performance Specifications

Nominal grid tie voltage	600Vac
Maximum continuous AC current	9.7A
Rated output power -20°C to +50°C	10kWac
Nominal frequency	60Hz
DC maximum power tracking range	900Vdc to 1800Vdc
Maximum open circuit voltage	1800Vdc
CEC average weighted conversion efficiency	>97.5%
Standby losses	<10W
Topology	Single conversion
Dimensions	970mm L x 270mm H x 140mm D target (2) 38.2" x 10.6" x 5.5"
Weight	40lbs (target value only)
Enclosure protection class	IP67 / Nema 6
Ambient temperature range	-20°C to +50°C
Cooling	Natural convection
Installation requirements	Shaded from direct sunlight
Ground fault protection	1A nominal
Communications	Isolated Modbus, Ethernet or Wi-Fi
Current distortion	Per IEEE1547

Subtask 2.2 – Electrical Design

The subcontractor drafted formal Electrical Schematics based on the existing preliminary electrical design, performed design calculations, as well as component part cost-performance-availability tradeoff analysis. Three magnetic components were designed as well. The quantifiable metrics necessary to verify the adequacy of this electrical design are:

Formal Electrical Schematics, component specifications via formal Bills of Materials and Magnetics Component Fabrication Drawings are complete.

An updated, detailed loss analysis indicates >98% CEC conversion efficiency at nominal DC buss voltage (1150Vdc).

An updated, costed BOM supports a total parts cost of <\$0.10 per Watt in 1k quantities based on current vendor quotations.

This Task resulted in circuit designs, component specifications, defined subassembly architectures and interconnection signal maps defined sufficiently to begin three circuit board layouts in Subtask 2.3 and to procure parts.

Subtask 2.3 – Printed Circuit Board Layout

The subcontractor completed the layout of two power boards (PB1 and PB2) and one control board (CB). Printed circuit boards, voltage clearance maps and a spacing requirements table were delivered to NREL for verification. The quantifiable metrics necessary to verify the adequacy of the layout of the printed circuit boards are: Physical fit of all components and traces on a PCB of predetermined size; border margins of ≥ 2 mm; layer-to-layer insulation thickness .008” between +buss, -buss and neutral; and voltage spacings greater than specified in the subcontractor-supplied table. This subtask resulted in highly manufacturable PCB assemblies, designed for UL and CE code compliance, PCBs ready to be loaded with components.

Subtask 2.4 – Procurement of Components and Prototype Inverter Fabrication

The subcontractor procured applicable vendor and component parts for six prototype inverters and completely assembled two non-functional prototype inverters. The construction and packaging of the inverter included the Power PCB Assembly 1 (PBA1), Power PCB Assembly 2 (PBA2), Control Board PCB Assembly (CBA), Magnetics Assembly (MAG) and Base Chassis Assembly (BCA).

Task 3 – Inverter Software Design

The subcontractor completed Version 0 of the inverter source code including:

Software Architecture Design – overall software architecture and specification of each of the modules.

Measurement Algorithms – design and code for all measurement algorithms, including: voltage (AC and DC), frequency, current, and power.

Phase Locked Loop (PLL) – design and code for the phase locked loop (PLL) required to synchronize the inverter to the grid.

Synchronous Frame AC Current Controller – design and code for the three-phase synchronous frame current regulation algorithms to regulate inverter current with appropriate phase into the grid.

PWM Generation – design and code for the PWM generation algorithms for the three level neutral point clamp (3LNPC) inverter.

DC Buss Voltage Control and MPPT – design and code for the algorithms required to control DC buss voltage and provide Maximum Power Point Tracking (MPPT) from the PV array.

Capacitor Voltage Balance Controller – design and code for the algorithm required to maintain capacitor voltage balance within 10% in the 3LNPC inverter.

Active Islanding Detection – design and code for algorithms required to actively detect an islanded operating condition and stop export of power in compliance of island detection within 2 seconds under conditions as described in UL1741/IEEE1547 requirements.

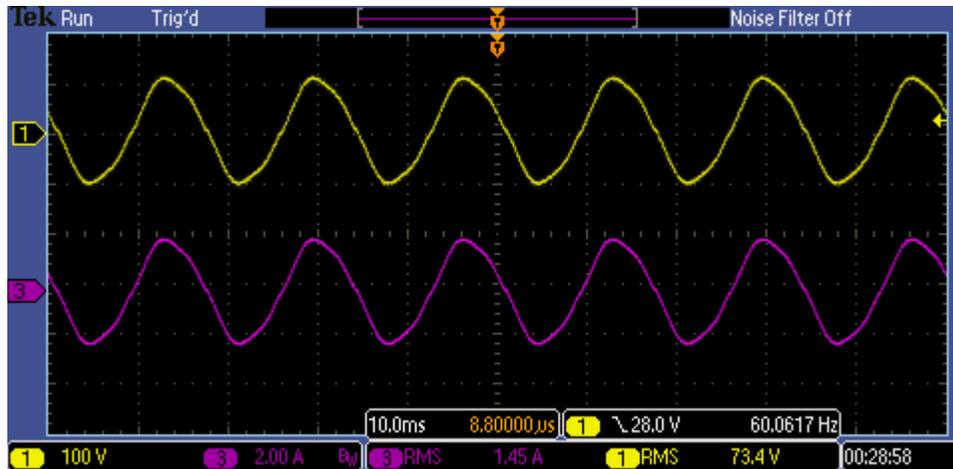
Harmonic Distortion Compensation – design and code for algorithms required to achieve low current harmonic distortion of less than 3% for each harmonic in compliance with UL1741/IEEE519.

Protective Relay Functions - design and code for protective relay functions operating at proper OV/UV, OF/UF set points required to monitor the grid and stop export of power in compliance with UL1741/IEEE1547.

Fault Handling – design and code for overall fault handling functions of the inverter with fault current limited to 120% of max steady state operating current.

Communications – design and code for MODBUS communications architecture and protocol (RS485) for the inverter.

As verification of Task 3, the inverter regulated three-phase current and DC buss voltage balance under software control into a resistive load at low buss voltages and in a stable manner. The inverter also transmitted AC current amplitude and DC bus voltage data to an external PC and received serial data commands from an external controller to turn the inverter on and off and to adjust the AC current amplitude. The result of this task effort was to code the bulk of the software “blind” without the benefit of fully functional target hardware so that that Task 4 may be fully supported. The “commented” source code listing was available for examination at the subcontractor’s facility but was not (or was ever intended to be) a deliverable because of sensitive IP content.



Oscillograph 1 – Initial Open Loop Current Regulation

Initial testing involved verifying the inverter’s basic capability to regulate sinusoidal current under software control. For these tests, the inverter was run at low power, from low DC bus voltages into a resistive three-phase load. These initial tests were done “open-loop” with no feedback to compensate for power system non-linearities, such as the change in line filter inductance as a function of current. Oscillograph 1 shows a distorted but essentially sinusoidal current of 1.45Arms. The other two phases (not shown) of this three phase system are substantially equivalent, only shifted in phase by 120 degrees each.

Task 4 – Inverter Design Verification Testing

The subcontractor completed bench-testing, troubleshooting, hardware/software integration, hardware retrofit and substantially demonstrated design verification. In this Task, the Subtasks are dependent and serial and therefore were used more as an outline test plan. The Deliverable could not be achieved without doing the best possible work on each subtask. This task included a significant number of software and hardware changes as part of this iterative and time-intensive process. This Task resulted in a definitive verification of the key inverter performance parameters; the stability of all the current regulation loops, the mitigation of protection circuit nuisance trips, conversion efficiency, power quality and temperature rise. This task consisted of four subtasks.

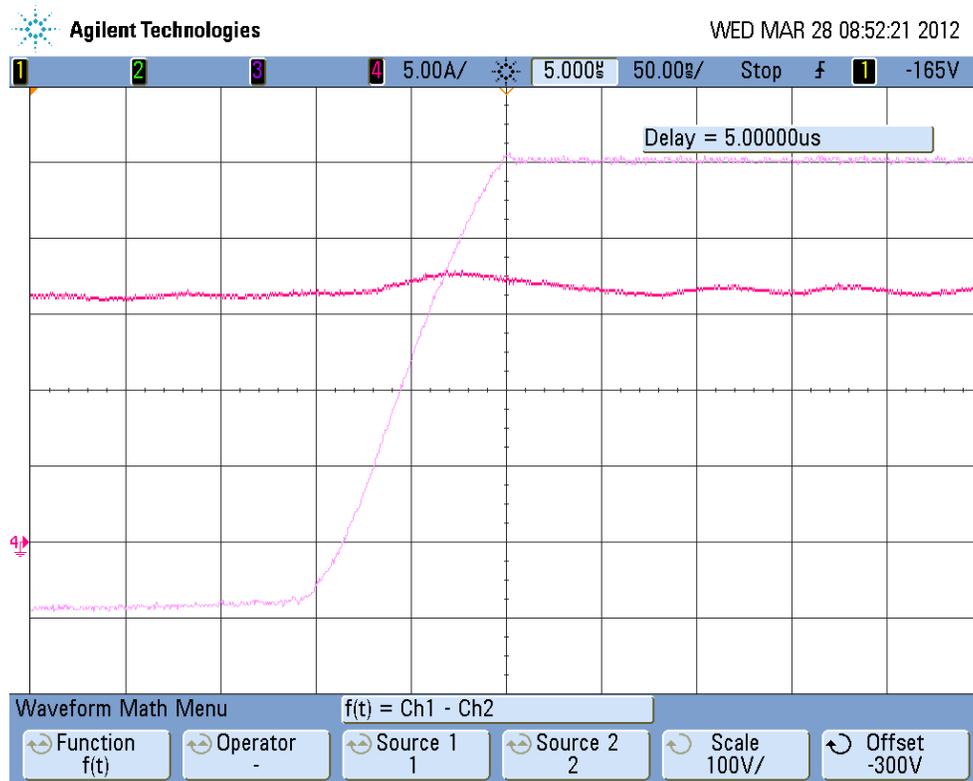
Subtask 4.1 – Protection Circuit

The subcontractor optimized the common mode noise rejection, response time and trip level verses the probability of nuisance trip for the following nine fault detection circuits; overvoltage positive DC buss, overvoltage negative DC buss, three overvoltage AC line-to-line voltages, three AC line overcurrents and ground fault current. In all cases, the combination of response time and trip level protected all components from damaging voltages or currents.

Subtask 4.2 – Gate Drive and DC Buss Impedance Verification

The subcontractor verified the proper operation of the inverter gate drive circuits, dead-time and isolation. As part of this process, a pulse test fixture was designed and fabricated to pulse each semiconductor, drive circuit and local DC buss impedance at full rated voltage and current. The timing and voltage overshoot on each device was monitored and recorded. The dead-time was adjusted per the Functional Specification, the required isolation was verified with a hi-pot tester,

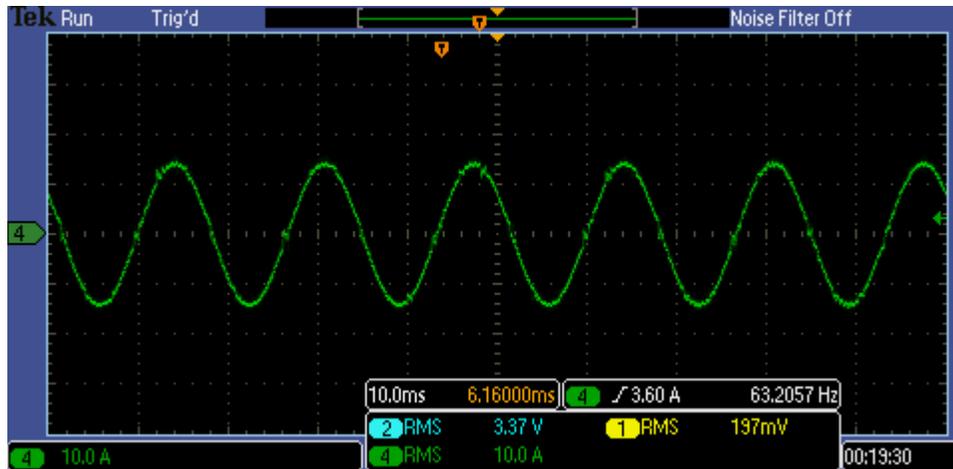
and the measured worst case overshoot was 30 Volts peak (the requirement was <200Vpk). This subtask verified that all semiconductor turn-off voltages are clamped to safe values and verified that the switches can reliably switch at high frequencies in the next subtask.



Oscilloscope 2 - IGBT Voltage Overshoot

Subtask 4.3 – AC Current Regulation Tests

The subcontractor investigated inverter full load current regulation. Testing began at low bus voltages into an output short circuit and progressed to rated bus voltages and output currents. Thereafter, the same process was repeated using resistive loads. The inverter regulated full load current in a stable manner at ≥ 9.7 Arms and Total Harmonic Distortion <5%. This subtask is resulted in current regulation feedback loop performance sufficient to proceed with grid-tied testing.

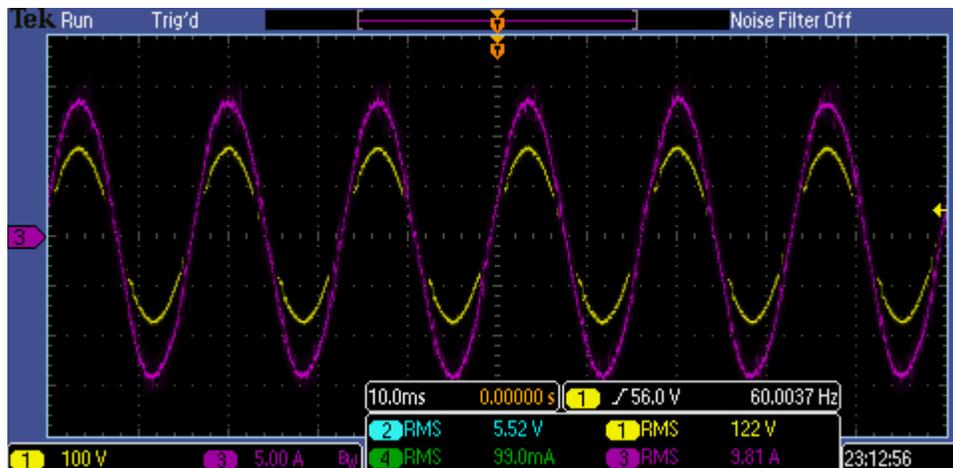


Oscilloscope 3 – Initial Closed Loop Current Regulation

Oscilloscope 3 shows inverter operation at low power from a low voltage DC buss and with the feedback loop closed. The inverter is producing low distortion sinewaves at 10Arms, slightly higher than the rated inverter current of 9.6Arms. The improvement in sinewave quality and the increase in amplitude shown in Oscilloscope 1, when compared to Oscilloscope 3, were achieved over a number of weeks and with a significant number of control software iterations.

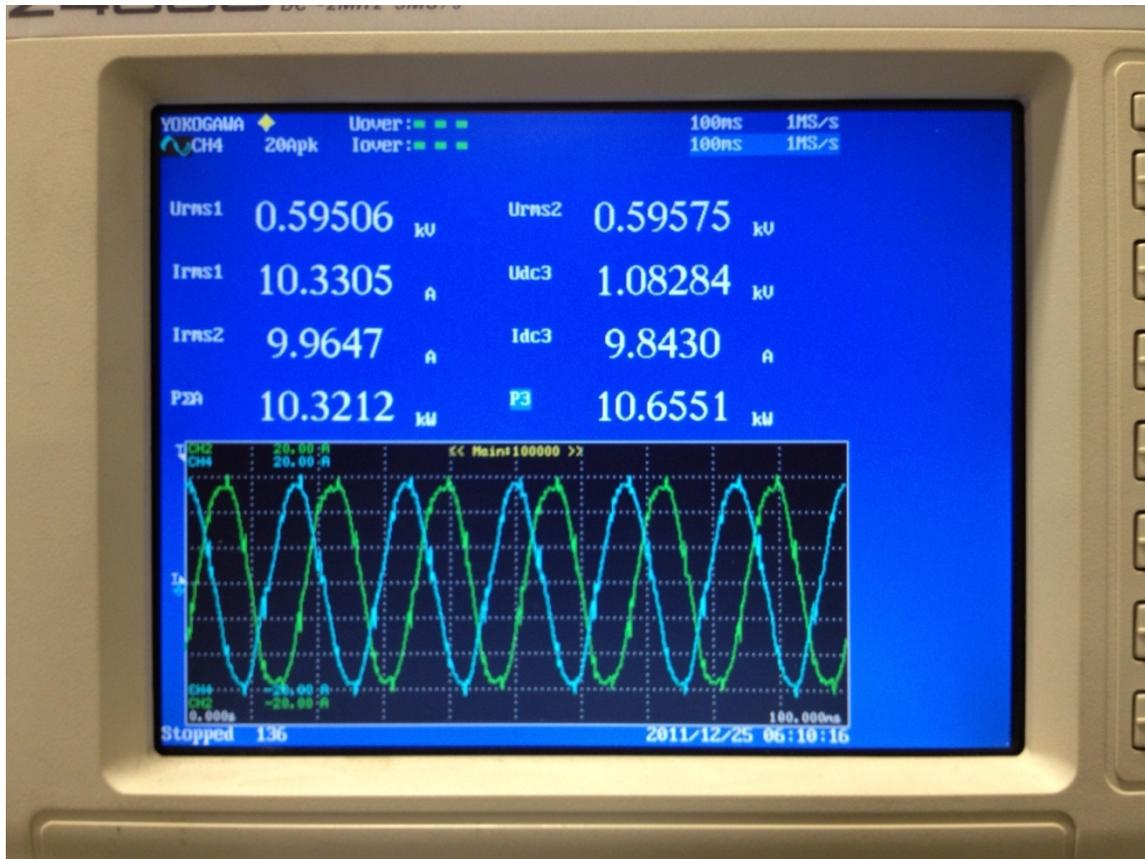
Subtask 4.4 – Full Power Grid-Tied Tests

The subcontractor investigated inverter operational characteristics when grid-tied at full power. All key performance metrics were achieved including; (i) stable grid-tied operation at 10kW into a 600Vac utility grid, (ii) CEC average weighted conversion efficiency greater than 97.5%, (iii) Total Harmonic Distortion less than 5% and (iv) temperature rise less than 30°C at 8kW. Achievement of these results was a major risk mitigation milestone and essentially the proof-of-concept for the inverter.



Oscilloscope 4 – Full Current Regulation at 208Vac Grid Tie

Oscillograph 4 shows grid-tied operation of the inverter as it sources ~3.6kW into the 120/208Vac utility grid. The magenta trace is one of the three phase currents and the yellow trace is the associated line-to-neutral voltage. The magenta (current) and yellow (voltage) traces are in phase, indicating substantially unity power factor power transfer. First-time grid-tied operation of any new inverter platform presents a significant challenge, because high fault currents are available from the utility grid. In addition, when grid-tied, the regulation control loop is much more difficult to operate in a stable manner and with sufficient loop gain to provide low distortion sinewaves.



Oscillograph 5 – Full Power Operation at 600Vac Grid Tie

Oscillograph 5 shows the operation of the inverter at full power operating into a 600Vac utility grid. This oscillograph shows two of the three phase line currents.

Task 5 – Regulatory Compliance Testing

The subcontractor opened a project with Underwriter’s Laboratories to begin the regulatory compliance testing process per UL1741. A project engineer has been assigned by UL. The subcontractor negotiated clearance and creepage voltage spacing with UL for this product which operates at substantially higher DC voltages compared to any inverter previously evaluated by UL. The subcontractor also submitted all electrical schematics, printed wiring assembly bills of materials. The progress is ongoing and the UL listing process will be completed outside of the scope of this subcontract as anticipated in the subcontract Statement of Work.

Task 6 – Final Inverter Deliverable

There are four key performance metrics for the final inverter deliverable. The values in parentheses are the actual final measured values. In all cases, performance expectations were met or exceeded.

CEC average weighted conversion efficiency >97.5%	[98% actual]
Total Harmonic Distortion <5% at 10kWac	[3.2% actual]
Temperature Rise <30°C at 8kW	[13°C actual]
Automatic Volt-VAR generation	[VV11 successfully tested]

Final Performance Metric 1 – CEC Power Conversion Efficiency

The test method used was the CEC Performance Test Protocol for Evaluating Inverters Used in Grid-Connected Photovoltaic Systems.

Test Equipment

DC power source, zero to ± 900 Vdc at 15 Amps minimum

Power analyzer, Yokogawa WT1600 with six high current input modules installed

Power resistors, 6 Ohms, capable of continuous operation at 10 Adc

Transformer, 15kVA, 208Y120 to 600Y346

Input Power

Input power was supplied by the adjustable voltage DC power supply. A resistor with a value of 6 Ohms was connected in series with each pole of the DC power source to decouple the power supplies from the inverter and to provide a higher impedance source, similar to a PV string impedance at normal operating voltages.

Input power to the PV1 input of the inverter was connected through channel 1 of the power analyzer, and input power to the PV2 input of the inverter was connected through channel 2 of the power analyzer. Currents were measured using the internal shunts and voltage was sensed on the inverter side of each shunt. Voltage was measured at the supply end of the power cables, so the loss in these cables was included in the measured inverter losses.

Output Power

Output power from the inverter was connected to the utility grid at 600Vac, supplied by the 15kVA transformer. Line 1 (Phase A) was connected through channel 3 of the power analyzer, line 2 through channel 4, and line 3 through channel 5. Voltage and current measurements were connected in the same manner as the input power.

Test Method

The inverter was operated at 3 input voltage and 6 power levels, for a total of 18 test conditions. The input voltages were:

Minimum	±450 Vdc (900 Vdc bus voltage)
Nominal	±518 Vdc (1,036 Vdc bus voltage)
Maximum	±720 Vdc (1,440 Vdc bus voltage)

The output power levels were:

10%	1.0 kWac
20%	2.0 kWac
30%	3.0 kWac
50%	5.0 kWac
75%	7.5 kWac
100%	10.0 kWac

Procedure

The input voltage was adjusted to the maximum rated operating voltage of ±720Vdc and the output power was adjusted to 100%. The inverter was allowed to run at these conditions for 2 hours, which has previously been established as the time to thermal equilibrium. The output power, input voltage, and efficiency were measured and recorded 5 times under this operating condition at 10 second intervals. This measurement was repeated for each of the six power levels specified above. These measurements were repeated for the nominal input voltage and the minimum input voltage.

Data Collection

See Appendix C for a listing of the raw conversion efficiency data.

Efficiency Weighting

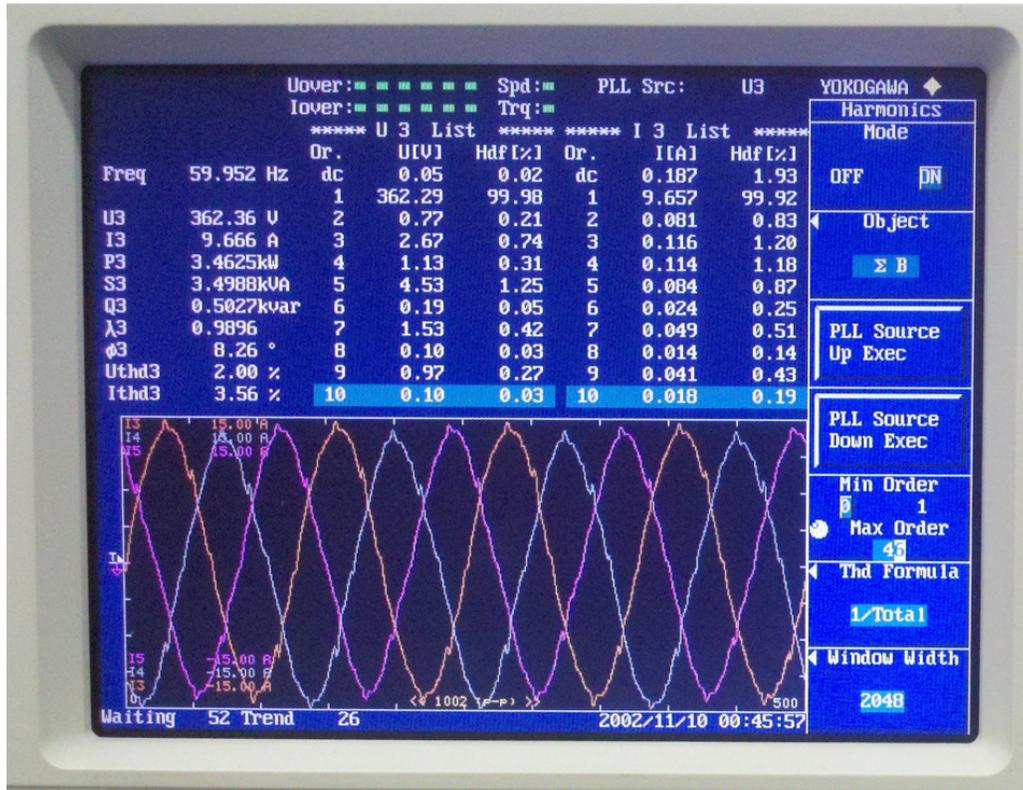
The five measurement groups were averaged and weighting factors were applied:

Input Voltage (Vdc)	Power Level (% , kW)						Weighted
	10%	20%	30%	50%	75%	100%	
Vmin +/-450	95.518	97.228	97.770	98.130	98.220	98.218	97.99%
Vnom +/-518	95.478	97.178	97.676	98.056	98.188	98.186	97.94%
Vmax +/-720	94.374	96.352	97.114	97.716	97.902	97.930	97.55%

weight	Factors						Sum
	10%	20%	30%	50%	75%	100%	
Vmin	3.821	4.861	11.732	20.607	52.057	4.911	97.99%
Vnom	3.819	4.859	11.721	20.592	52.040	4.909	97.94%
Vmax	3.775	4.818	11.654	20.520	51.888	4.897	97.55%
CEC efficiency = 98%.							

Final Performance Metric 2 – Total Harmonic Distortion

Ideal THD testing requires a “clean,” undistorted utility grid so that harmonics produced by any 60Hz utility voltage distortion will not interact with the inverter output filter and produce current distortion not sourced from the inverter. Efforts had been made to reduce the grid voltage distortion at the inverter point of interconnection, however, at the time of witness testing, the utility voltage THD was 2%.



Oscillograph 6 – Voltage and Current Distortion Data

The inverter current total harmonic distortion was measured at 3.56% when operating into a utility grid having a voltage total harmonic voltage distortion of 2.00%. Since the current THD is allowed to be 2.5% greater than the utility grid voltage THD, the inverter operated as desired. The requirement is <5% THD and the measured and utility-voltage-distortion-compensated value is 1.6%.

Final Performance Metric 3 – Temperature Rise

The initial temperature rise at a power level of 8kWac and at nominal buss voltage was measured at 14°C above ambient, significantly below the specified limit of 30°C. The test was repeated at 100% power and with the DC buss voltage increased to 1100Vdc. The temperature rise under these conditions was 18°C above ambient. In both cases, the inverter was run for over an hour in order to achieve thermal stability.

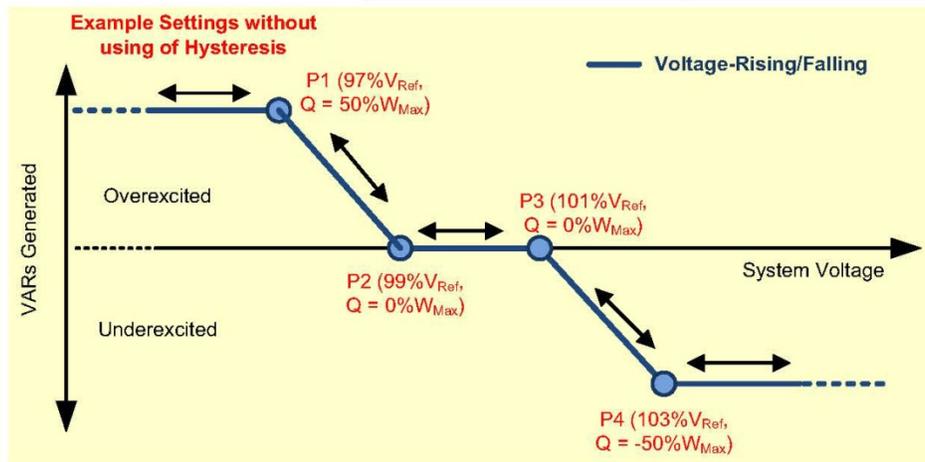
Final Performance Metric 4 – Automatic Volt-VAR generation

The software was created and tested by the subcontractor to program the prototype inverter to generate VARs as a function of grid tie voltage. The inverter functioned as expected.

Example Settings

Voltage Array (% VRef)	VAR Array (% WMax)
V1 97	Q1 50
V2 99	Q2 0
V3 101	Q3 0
V4 103	Q4 -50

VAR Ramp Rate Limit – fastest allowed decrease in VAR output in response to either power or voltage changes	50 [%WMax/second]
VAR Ramp Rate Limit – fastest allowed increase in VAR output in response to either power or voltage changes	50 [%WMax/second]
The time of the PT1 in seconds (time to accomplish a change of 95%).	10 seconds
Randomization Interval – time window over which mode or setting changes are to be made effective	60 seconds



Graphic 1 – Inverter Volt-VAR Example

The screenshot shows the "Volt-VAR Mode (VV11) Edit Form" with the following settings:

- WMax:** 3600 Watts
- Rate of Change:** 2.0 % I reactive/sec
- Hysteresis:** 0.5 % I reactive
- Interval:** 5 Seconds
- Voltage (% VRef) / VAR (% WMax) settings:**
 - 0.0 / 0.0 (with Enter button)
 - 92 / 50 (with Remove button)
 - 98 / 0
 - 102 / 0
 - 108 / -50

Buttons for "OK" and "Cancel" are also visible.

Graphic 2 – Prototype Inverter User Interface VV11 Programming

Commercialization

The proposed inverter hardware platform is extremely flexible. Input voltages from 1000Vdc floating to 2000Vdc bipolar can be accommodated as well as output voltages of 400, 480, 600 and 690 by only changing the control software and in some cases the DC buss capacitor and filter inductor values. Four products will be offered, all based on the same platform:

Common Inverter Product Specifications

Nominal Power Rating	10.0 kW
Topology	Single conversion
PV Configuration	Bipolar
CEC Conversion Efficiency	98%
LVRT, VAR and Volt-VAR Capable	Yes
Transformerless	Yes
Environmental Integrity	IP67 / Nema 6
Operating Temperature Range	-20°C to +50°C
Cooling	Natural convection
Dimensions, without skirt	36" x 8" x 3"
Weight	50 - 60 lbs
Design Life	20 - 25 years

Model-Specific Specifications

Model Number	Input Voltage, Max Voc	Grid Tie Voltage
MM10-600	±900	600
MM10-480	±600	480
MM10-400	1000	400
MM10-480-FS	Asym Bipolar +1000 and -500	480 delta only

Competitors

The PV inverter market is already extremely competitive and expected to become even more so as the price of the PV modules continues to decline, putting more cost pressure on BOS components. At present, there are no commercial product offerings that approach the performance, cost and longevity advantages of macro-micro inverter platform in multi-megawatt systems with respect to enabling the overall lowest LCOE.

The proposed inverter will also be very cost effective at 480Vac and 400Vac grid-tie for smaller commercial systems.

Summary

The game-changing and disruptive qualities of the Macro-Micro inverter are two-fold. First, the inverter is installed in utility-scale systems as an indestructible “brick” along with the solar modules and neither is touched for the next 25 years. There is no other inverter on the market with this potential or with higher input and output voltages for enhanced system power collection efficiencies. Second, because of the modularity and flexibility of this approach, approximately one-half of all non-residential PV capacity could be served with essentially one inverter.

The Inverter Key Performance Parameters are:

Cost - Overall inverter cost reduction of 50%-75% with respect to inverter-driven LCOE over the life of a PV system.

Performance - Highest conversion efficiency at the 10kW power level, 98% CEC, baseline is 95%-97%. Enables PV system solutions with 72% less copper while eliminating the potential for high energy DC arc faults.

Reliability - The usable inverter lifetime is doubled or tripled to 25 years, with respect to a baseline reference of 8-12 years.

Scalability - The Micro-Macro manufacturer need only support one hardware platform to serve customer requirements from 10kW to multi-megawatts.

Conclusion

Is it possible to develop one new modular inverter for all PV systems greater than 10kW that would substantially outperform, with respect to LCOE, and therefore essentially replace all existing 3-phase PV inverters of any size?

Initially, this was not the goal or premise of this development effort but as design-based performance and cost data were accumulated and prior-art system design comparisons were made, it became difficult to find any limitations or deficiencies in the proposed power converter and associated system solutions to deny this possibility.

Appendix A

10MW PV POWER PLANT LCOE COMPARISON CENTRAL INVERTERS vs DISTRIBUTED STRING INVERTERS

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Subcontract No. NEU-2-11979-04

All supporting data used in this report was acquired, interpreted and presented in good faith and is considered accurate by the author. However, if there is a conflict in this report between the cost or performance data of equipment manufactured by others and that manufacturer's data, consider the manufacturer's data as being the most accurate and current.

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Overview

Two photovoltaic power systems are compared to quantify the cost efficiency of using a distributed string inverter approach over a central inverter approach in multi-megawatt systems. Each distributed inverter converts power from a single bipolar string of modules to three-phase 600Vac, enabling system AC intrafield power collection. Each central inverter converts power from a plurality of ungrounded PV strings by typical DC intrafield power collection methods.

A base model LCOE of \$0.12/kWh, a system installation cost of \$3.65/Wdc nameplate and an inverter cost of \$0.24/W will be used as the central inverter base-line reference datum. Best of class 550kW central inverters with CEC conversion efficiencies of 97 % and 1000V input capability have been specified.

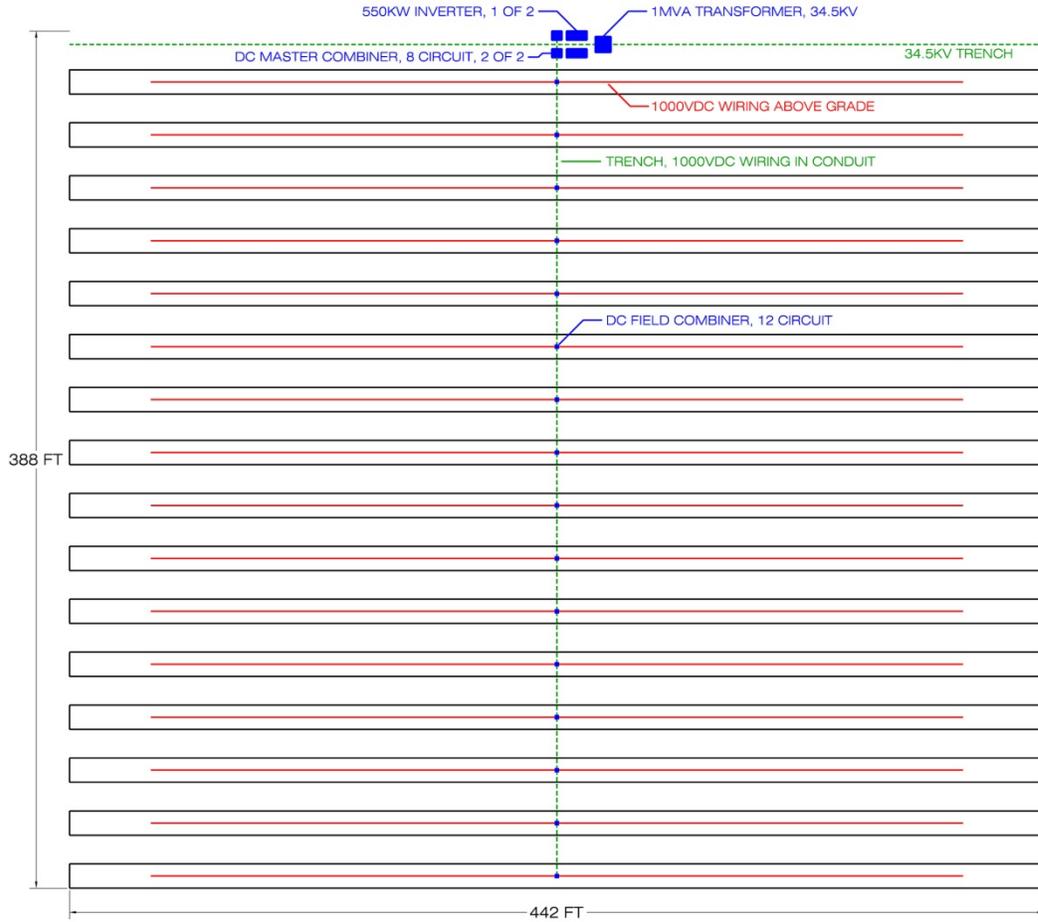
The cost comparison will only include differences in the two systems since the cost of PV modules, racking and distribution transformers is essentially the same for both system solutions. The costs will be quantified by breaking down dissimilar system equipment into four categories; (i) field wiring, (ii) low current “field” circuit combiners, (iii) high current “master” circuit combiners and (iv) inverters. In addition, system differences in power conversion and energy harvest efficiencies will be valued at \$3.65/W, the base system installed cost.

System Designs

Both systems are designed with Kyocera 315W polycrystalline modules on fixed-tilt racking. The nominal system ratings are 10MW DC nameplate. Figure 1 and Figure 2 show field layout and electrical one-line diagrams for a central inverter solution 1MW block, respectively. Figure 3 and Figure 4 show field layout and electrical one-line diagrams for a distributed inverter solution 1MW block, respectively. The row lengths, number of rows and therefore the overall layout geometry, for each solution, are determined by the PV string lengths of each system. RPC also performed similar comparisons using Suntech 280W modules and First-Solar 80W modules, both yielded essentially equivalent end results.

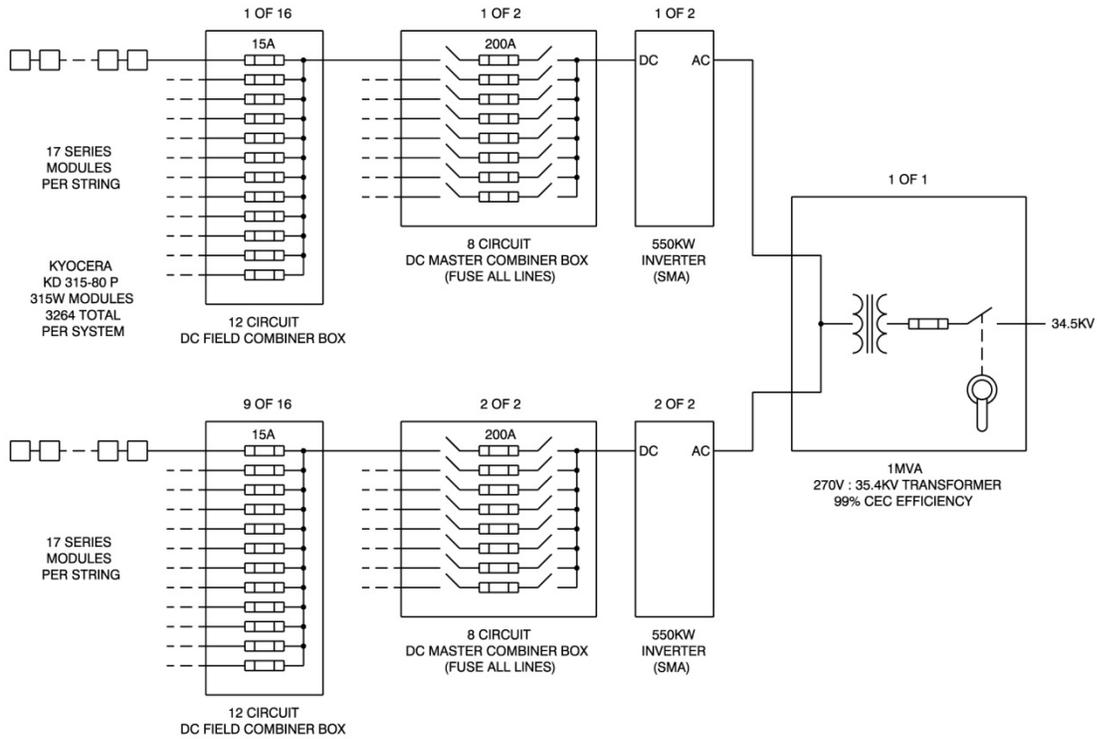
In Figure 1 the inverters, transformers and associated equipment are located north of the entire array field to prevent the inverter from shadowing the array at lower sun angles. In Figure 3 the transformer and AC master combiner may be located close to the center of the field because the enclosure heights are close to the array height above grade and maintenance access is not required. In both system solutions, the clear space between rows is 14 feet to provide access to field components.

FIGURE 1
 1MW PHOTOVOLTAIC POWER SYSTEM BUILDING BLOCK LAYOUT
 USING KYOCERA 315W MULTICRYSTAL MODULES
 AND TWO 550KW CENTRAL INVERTERS



SYSTEM EQUIPMENT LIST	
3264	KYOCERA MODEL 315-80P 315W MODULES
2	550KW INVERTERS
16	LOW CURRENT DC FIELD COMBINER BOXES, 12 CIRCUIT
2	HIGH CURRENT DC MASTER COMBINER BOXES, 8 CIRCUIT
1	DISTRIBUTION TRANSFORMER, 1MVA 34.5KV

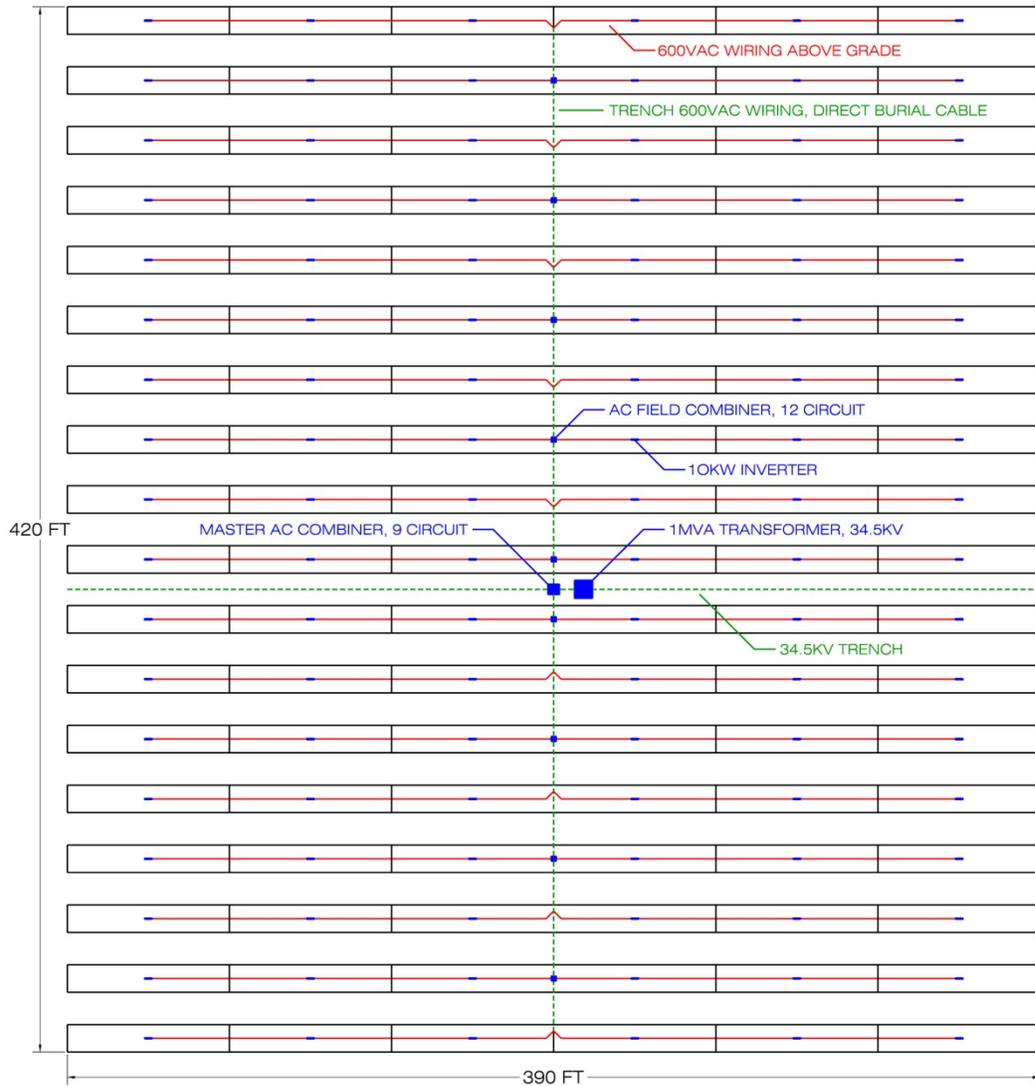
FIGURE 2
 NOMINAL 1MW PHOTOVOLTAIC POWER SYSTEM BUILDING BLOCK
 BASED ON KYOCERA KD 315-80 P MODULES AND TWO CENTRAL INVERTERS



DC SYSTEM PERFORMANCE

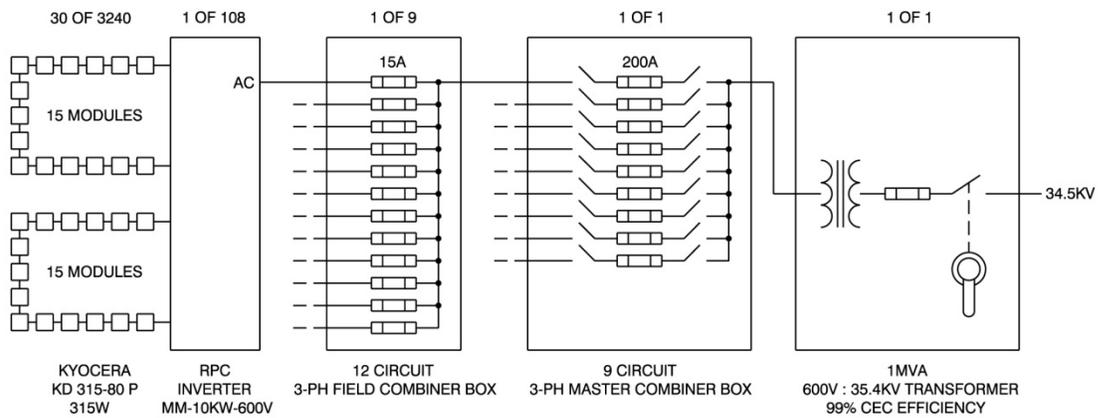
DC NAMEPLATE = 1.02 MEGAWATTS
 20degC AMBIENT, 1000W/sq M = 891KWDC
 45degC AMBIENT, 1000W/sq M = 760KWDC
 Voc @ -30degC = 1000V
 Vmpp @ 45degC, 800W/sq M = 518Vdc

FIGURE 3
 1MW PHOTOVOLTAIC POWER SYSTEM BUILDING BLOCK LAYOUT
 USING KYOCERA 315W MULTICRYSTAL MODULES
 AND DISTRIBUTED RPC 10KW INVERTERS



SYSTEM EQUIPMENT LIST	
3240	KYOCERA MODEL 315-80P 315W MODULES
108	RPC MODEL MM-10K-600V MACRO-MICRO INVERTERS
9	LOW CURRENT AC FIELD COMBINER BOXES, 12 CIRCUIT
1	HIGH CURRENT AC MASTER COMBINER BOX, 9 CIRCUIT
1	DISTRIBUTION TRANSFORMER, 1MVA 34.5KV

FIGURE 4
 NOMINAL 1MW PHOTOVOLTAIC POWER SYSTEM BUILDING BLOCK
 BASED ON KYOCERA KD 315-80 P MODULES AND RPC DISTRIBUTED INVERTERS



DC SYSTEM PERFORMANCE

DC NAMEPLATE = 1.02 MEGAWATTS
 20degC AMBIENT, 1000W/sq M = 904KWDC
 45degC AMBIENT, 1000W/sq M = 791KWDC
 Voc @ -40degC = +/- 910V
 Vmpp @ 45degC , 800W/sq M = 915Vdc pole-to-pole

Field Wiring

In both systems, the field wiring is done in two tiers, low current and high current. In the central inverter system, 12 low current strings of modules are combined at each row center at a DC field combiner box. The high current (12X higher) output of the field combiner box is a circuit to a DC master combiner input and is typically called a “home run”. The low current string conductors are pairs of #12AWG Type PV run in open air and the high current home runs are 2/0 type RHW-2 2KV run in underground PVC conduit. In the distributed inverter system, 12 low current 3-phase AC inverter output circuits are combined at an AC field combiner box. The high current (12X by coincidence only) output of the AC field combiner box is the circuit to the AC master combiner input. The low current inverter output conductors are grouped within an armored, direct burial 3-conductor cable and run in open air or underground between rows. The high current AC conductors are 2/0 of the same cable type, buried without conduit.

The central inverter system conductors are sized for 1% resistive losses at nominal solar conditions. The distributed inverter conductors are sized for a worst-case voltage drop of ~1% on the longest conductor path to an inverter and have average resistive losses of 0.65%.

All conductor run lengths are taken from the scaled layout drawings in Figures 1 and 3.

For a 1MW building block, the central inverter system requires 4564 lbs of copper, the distributed inverter system requires 2844 lbs. The delta per 1MW building block is 1720 lbs of copper at \$3.75/lb or \$6450 and 3300’ of 3” conduit at \$0.96/ft or \$3170. The net wiring hardware cost advantage is **\$9620**. The value of the efficiency advantage is 0.35% x 1MW x \$3.65/W or **\$12,775**.

Other Factors - This analysis does not take into account the cost of interim-run pull boxes for high DC current runs, 384 MC4 connectors and the labor cost to pull cables through conduit and make the MC4 terminations in the central inverter solution.

Low Current Field Combiner Boxes

In both systems, the hardware components for both the DC and AC low current combiner boxes are essentially the same; DIN-rail-mounted touch-safe, midget fuse holders and buss bars mounted in a Nema 3R enclosure. The number of fuses per box and the fuse types are, however, different. For a 1MW building block, the central inverter system requires 192 fuses rated at 15A, 1000Vdc, 20kA and the distributed inverter system requires 324 fuses rated at 15A, 600Vac, 100kA.

Table 1 – Field Combiner Cost Comparison per MW
Distributed – Central (baseline ref)

Component	Part #	System	Qty	\$ Ea	Ext k\$	k\$Δ
Fuse 15A 1kVdc	SPF15	Cent	192	16.00	3.1	-1.7
Fuse 15A 600Vac	SC15	Dist	324	4.30	1.4	
Fuse holder	USM1	Cent	192	4.90	.9	+ .5
Fuse holder	USM1	Dist	324	4.90	1.6	
Total						-1.2

The net field combiner cost advantage is **\$1,200/MW** for the distributed inverter system using component quantity pricing for 10MW.

Other Factors - Practically speaking, the costs of 90 boxes vs. 160 boxes for the 10MW distributed vs. the central system, respectively, will be lower as will the labor to mount the boxes and attach conduits to the DC, central system combiner boxes.

High Current Master Combiner Boxes

Both the central inverter system DC and the distributed inverter system AC master combiner boxes include overcurrent protection and “home run” source circuit load-break disconnect functions. There are significant cost differences. First, in ungrounded DC systems (the central inverter system) both current carrying conductors need to be fused, although this is not shown in the one-line diagrams. Second, the cost of 1000Vdc fuses vs. 600Vac fuses is greater because a DC arc is much harder to interrupt than an AC arc. Third, a disconnect switch capable of DC load-break at 1000Vdc is more costly than a common 600Vac rated switch.

In the central inverter system, 32 fuses and 16 disconnect switches are required capable of clearing/breaking 1000Vdc under worst case load conditions. In the distributed inverter system, 27 fuses and 9 three-phase disconnect switches are required capable of clearing/breaking 600Vac under load.

**Table 2 – Master Combiner Cost Comparison per MW
Distributed – Central (baseline ref)**

Component	Part #	System	Qty	\$ Ea	Ext k\$	k\$Δ
Fuse 200A 1kVdc	A150X200	Cent	32	250	8.0	-5.7
Fuse 200A 600Vac	IDSR200	Dist	27	86	2.3	
Switch 200A 1kVdc	REHU494IP	Cent	16	2062	33.0	-24.2
Switch 200A 600Vac	H364RB	Dist	9	1247	11.2	
Total						-21.8

The net master combiner cost advantage is **\$21,800/MW** for the distributed inverter system using component quantity pricing for 10MW.

Other Factors – It should be noted that in the distributed inverter system the maximum DC arc fault energy is limited to less than 1% of the array capacity verses 50% (½MW) for the central solution.

Inverters

The central inverter solution uses two force-convection-cooled, IP54 rated, 550kW inverters that essentially must be replaced every 10 years and must also be subject to a scheduled maintenance plan to replace cooling fans, to remove particulate contamination and to mitigate moisture related corrosion issues. With the stated replacement and maintenance schedule, a 2% failure rate per 15 years is anticipated by the manufacturer.

The distributed inverter solution uses 108 natural-convection-cooled, IP67 rated, 10kW inverters. The anticipated, maintenance-free failure rate is 2% in 15 years and 8% in 25 years. It should be noted that the 10kW inverters can be replaced by unskilled workers (plug-and-play) and that the energy lost by a single failed 10kW inverter in a 10MW system is negligible compared to the loss of a single 550W inverter.

In both cases, the 550kW and 10kW inverter power ratings are peak power capability at 25°C ambient. Power conversion efficiencies are 97%* and 98%, respectively.

**Table 3 – 25 Year Inverter Cost Comparison per MW
Distributed – Central (baseline ref)**

Category	Inverter	System	Qty	\$ Ea	Ext k\$	k\$Δ
Original Cost	550kW	Cent	2	120,000	240	+84
	10kW	Dist	108	3,000	324	
Scheduled Replacement	550kW	Cent	2 x 1.5	120,000	360	-360
	10kW	Dist	0	0	0	
Failure Replacement	550kW	Cent	3.3%	2 x 120,000	7.9	+18
	10kW	Dist	8%	108 x 3,000	25.9	
Maintenance	550kW	Cent	2†	15,000†	30	-30
	10kW	Dist	0	0	0	
Total						-288

**Table 4 – 25 Year Inverter Energy Harvest Comparison per MW
Distributed – Central (baseline ref)**

Category	Inverter	System	Qty	ΔWdc	\$/Wdc installed	k\$Δ
CEC Efficiency	550kW	Cent	97%*	10kW	3.65	-36.5
	10kW	Dist	98%			
MPPT Energy Harvest‡	550kW	Cent	0% ref	25kW	3.65	-91.3
	10kW	Dist	+2.5%			
Total Value						-127.8

The total value in Table 4 is based on how many more modules and BOS components would need to be installed in the central inverter system to achieve AC energy output parity with the distributed inverter system.

The net inverter cost advantage over the 25-year lifetime of the system is **\$415,800/MW** for the distributed inverter system using component quantity pricing for 10MW.

†An average maintenance cost of 5% of the inverter cost (original costs plus 1.5 replacements) per inverter is assumed over the 25 year life of the system. The actual cost will be site-specific.

*The manufacturer's data sheet (SMA in this case) specifies a 97.5% CEC weighted conversion efficiency without the losses associated with auxiliary power used to power control circuits, cooling fans and anti-condensation heaters. The 0.5% degradation in conversion efficiency is an assumed value.

‡ An estimated 2.5% in energy harvest is expected by using 108 versus 2 maximum power point trackers in the distributed inverter solution versus the central inverter solution, respectively. Finer MPPT granularity mitigates maximum power point inaccuracies due to module mismatch, microclimates in large area arrays, differential soiling and dissimilar module aging characteristics.

Summary

The LCOE for any PV system is site-specific and significantly dependent on the Power Purchase Agreement (PPA) rate structure and the project financing. In order to bring credible, real-world value to this comparative analysis, installation cost and energy forecasts were taken from the 550MW Topaz power plant in central California. The installation cost to 25-year cost ratio was determined using average values from a number of recently completed utility-scale projects.

This analysis indicates that an **8.2% reduction in LCOE**, from \$0.12/kWh to \$0.11/kWh, can be achieved using a system solution with RPC distributed string inverters when base-lined to a system solution using central inverters.

Table 5 shows the summary cost improvements by the compared hardware and performance categories.

**Table 5 – Summary Cost Reduction
10MWdc Nameplate Distributed Inverter System**

LCOE Cost Reduction	\$k/10MW
Field Wiring	96
Field Wiring Efficiency	128
Field Combiner Boxes	12
Master Combiner Boxes	218
Inverter Hardware	2880
Inverter Energy Harvest	1278
Total \$M	\$4.612M

Summary Calculations

Installed cost of \$36,500,000

Total 25 year cost of \$56,400,000 (Base model with 30% total interest, 8% total O&M)

Energy produced in 25 years of 470,000 MWh (0.5%/yr degradation)

Central Inverter System LCOE = \$0.1200 per kWh

Total 25 year cost of \$56,400,000 – \$4,612,000 = \$51,788,000

Distributed Inverter System LCOE = \$.1102 per kWh

8.2 % reduction in LCOE

Conclusion

This analysis quantifies the value of three key elements of a distributed string inverter system solution for utility-scale PV power plants, which together can reduce the system LCOE by 8.2%.

Maintenance free, high reliability, plug-and-play “disposable” string inverters

AC intrafield power collection vs. DC power collection

Fine, string-level, maximum power point tracking granularity

Appendix B

SYSTEM COPPER LOSS CALCULATIONS

Assertions have been made about enhanced system intrafield power collection efficiencies and a reduction in copper weight by 72% over some baseline value. The following tables and discussion describes the method used.

600Vdc vs. 600Vac 3-ph Intrafield Power Collection, per 10kW, per 1000' circuit

600Vdc (max open circuit)	600Vac (nominal) 3-phase
P = 10,000W / 97%*	P = 10,000W
Nominal voltage 384V	Nominal voltage 600V
# of conductors = 2	# of conductors = 3
Current per conductor = 26.8A _{dc}	Current per conductor = 9.63A _{rms}
Normalized loss figure = I ² x 2 = 1436	Normalized loss figure = I ² x 3 = 278
e.g. 1000' circuit #2AWG = 287W total	e.g. 1000' circuit #2AWG = 56W total

For essentially equivalent losses, the 600Vdc solution would require 350kcmil conductors compared to the 600Vac solution using #2AWG conductors or **3.6 times the weight and cost of copper.**

1000Vdc vs. 600Vac 3-ph Intrafield Power Collection, per 10kW, per 1000' circuit

1000Vdc (max open circuit)	600Vac (nominal) 3-phase
P = 10,000W / 97%*	P = 10,000W
Nominal voltage 640Vdc	Nominal voltage 600Vac
# of conductors = 2	# of conductors = 3
Current per conductor = 16.1A	Current per conductor = 9.63A _{rms}
Normalized loss figure = I ² x 2 = 519	Normalized loss figure = I ² x 3 = 278
e.g. 1000' circuit #2AWG = 104W total	e.g. 1000' circuit #2AWG = 56W total

For essentially equivalent losses, the 1000Vdc solution would require 2/0 conductors compared to the 600Vac solution using #2AWG conductors or **1.4 times the weight and cost of copper.**

The 1000Vdc/600Vac table does not, however, provide a valid cost comparison because of the significant price premium for 1000Vdc rated fuses and disconnect switches verses common 600Vac class rated equipment.

**Central inverter conversion efficiency*

For reference: #2AWG = .201Ω/kFT, 2/0 = .101Ω/kFT, 350kcmil = .0382Ω/kFT

Appendix C

RAW CEC POWER CONVERSION EFFICIENCY DATA

		Sample #1			Sample #2			Sample #3		
Output Power	Input Voltage	Output Power	Input Voltage		Output Power	Input Voltage	Efficiency	Output Power	Input Voltage	Efficiency
(%)	(Vdc)	(kW)	(Vdc)	(%)	(kW)	(Vdc)	(%)	(kW)	(Vdc)	(%)
10%	Vmin	0.97	449	95.50	0.97	449	95.49	0.97	449	95.52
20%	Vmin	2.03	449	97.20	2.03	449	97.23	2.03	449	97.24
30%	Vmin	2.98	451	97.78	2.98	451	97.77	2.98	451	97.79
50%	Vmin	4.98	449	98.13	4.98	449	98.12	4.98	449	98.13
75%	Vmin	7.50	450	98.21	7.50	450	98.22	7.50	450	98.23
100%	Vmin	10.01	451	98.22	10.01	451	98.22	10.01	451	98.22
10%	Vnom	1.00	517	95.46	1.00	517	95.48	1.00	517	95.49
20%	Vnom	2.08	517	97.18	2.08	517	97.18	2.08	517	97.17
30%	Vnom	3.00	517	97.67	3.00	517	97.67	3.00	517	97.69
50%	Vnom	5.05	517	98.05	5.05	517	98.06	5.05	517	98.06
75%	Vnom	7.57	518	98.19	7.57	518	98.18	7.57	518	98.19
100%	Vnom	10.11	518	98.18	10.11	518	98.19	10.11	518	98.19
10%	Vmax	1.00	721	94.37	1.00	721	94.38	1.00	721	94.38
20%	Vmax	2.04	721	96.35	2.04	721	96.36	2.04	721	96.36
30%	Vmax	3.03	720	97.11	3.03	720	97.11	3.03	720	97.12
50%	Vmax	5.01	720	97.71	5.01	720	97.72	5.01	720	97.72
75%	Vmax	7.54	720	97.90	7.54	720	97.90	7.54	720	97.90
100%	Vmax	10.01	721	97.93	10.01	721	97.93	10.01	721	97.93

		Sample #4			Sample #5		
Output Power	Input Voltage	Output Power	Input Voltage	Efficiency	Output Power	Input Voltage	Efficiency
(%)	(Vdc)	(kW)	(Vdc)	(%)	(W)	(Vdc)	(%)
10%	Vmin	0.97	449	95.55	0.97	449	95.53
20%	Vmin	2.03	449	97.23	2.03	449	97.24
30%	Vmin	2.98	451	97.75	2.98	451	97.76
50%	Vmin	4.98	449	98.14	4.98	449	98.13
75%	Vmin	7.50	450	98.22	7.50	450	98.22
100%	Vmin	10.01	451	98.21	10.01	451	98.22
10%	Vnom	1.00	517	95.47	1.00	517	95.49
20%	Vnom	2.08	517	97.19	2.08	517	97.17
30%	Vnom	3.00	517	97.67	3.00	517	97.68
50%	Vnom	5.05	517	98.06	5.05	517	98.05
75%	Vnom	7.57	518	98.19	7.57	518	98.19
100%	Vnom	10.11	518	98.19	10.11	518	98.18
10%	Vmax	1.00	721	94.36	1.00	721	94.38
20%	Vmax	2.04	721	96.35	2.04	721	96.34
30%	Vmax	3.03	720	97.11	3.03	720	97.12
50%	Vmax	5.01	720	97.72	5.01	720	97.71
75%	Vmax	7.54	720	97.90	7.54	720	97.91
100%	Vmax	10.01	721	97.93	10.01	721	97.93